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13. ABSTRACT (Maximum 200 words) This grant was funded for the purpose of (1) developing the methodology for measuring the microstructural properties of snow, (2) performing a series of experiments to calibrate the theory developed to measure snow microstructure, and (3) determining in detail how the material microstructure changes with time under uniform temperature conditions. Microstructure includes such parameters as grain size, grain shape, bond size, neck length, pore size, and 3-D coordination number (number of bonds per grain). An essential part of the project included support for a visiting scientist from Japan, Atsushi Sato, who had developed specialized equipment for producing very fine-grained snow with predominantly spherical grain shape. This snow allowed us to perform the experimental part of the project with more precision than using natural snow. The small grain size was responsible for the rapid metamorphism, and the spherical grain shape greatly simplified the task of calibrating the software developed to measure the snow microstructure. The objectives of the grant have been achieved. A number of papers have either been published or are now being written, and the formulation developed by the PI and his doctoral student has been shown to be a very effective method of measuring microstructure.				
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FINAL REPORT

Robert L. Brown

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**College of Graduate Studies
Montana State University
Bozeman, MT 59717**

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TABLE OF CONTENTS

1.0 Manuscripts Submitted or in Preparation	1
2.0 Scientific Personnel Supported	1
3.0 Inventions	1
4.0 Objectives of the Project	2
5.0 Summary of Results	2
6.0 Technology Transfer	6
7.0 Importance of Research to Army Mission	6

1.0 Manuscripts Submitted or in Preparation

Edens, M. Q. and R. L. Brown, "An experimental evaluation of changes in microstructure of fine-grained snow due to equi-temperature metamorphism", *Cold Regions Science and Technology*, (in preparation).

Edens, M. Q. and R. L. Brown, "Determination of bonding and neck geometry in cohesive granular materials", *Cold Regions Science and Technology*, (in preparation).

Brown, R. L., M. Q. Edens, and M. Barber, "Alterations in snow microstructure in layered nonhomogeneous snow cover", *Journal of Geophysical Research*, (in preparation).

Brown, R. L., M. Q. Edens, and M. Barber, "A mixture theory for mass transfer based upon microstructure", *AIChE Journal* (submitted).

Edens, M. Q., R. L. Brown, and M. Barber, "Surface segmentation and measurements of surface sections of snow", *Cold Regions Science and Technology*, (in press).

Brown, R. L., M. Q. Edens, and A. Sato, "Application of a mixture theory to equitemperature metamorphism of snow", *Proceedings of the 3rd International Conference on Snow Engineering*, Sendai, Japan, May 26-31, 1996.

Edens, M. Q. and R. L. brown, "Measurement of microstructure from surface sections", *Proceedings of the International Conference on Snow & its Ramifications*, Manali, India, September, 1994.

Brown, R. L., E. E. Adams, and M. Barber, "Non-equilibrium thermodynamics applied to metamorphism of snow", *Proceedings of the International Conference on Snow & its Ramifications*, Manali, India, September, 1994.

Sato, A., E. E. Adams and R. L. Brown, "Effect of microstructure on heat and vapor transport in snow composed of uniform fine ice spheres", *Proceedings of the International Snow Science Workshop*, Oct 1994, Salt Lake City, Utah.

Brown, R. L., M. Q. Edens, and A. Sato, "Metamorphism of fine-grained snow due to surface curvature differences", *Annals of Glaciology*, Vol. 19, pp. 69-76, 1994.

2.0 Scientific Personnel Supported

1. M. Q. Edens, Ph.D. student: expected to graduate May 1997.
2. R. L. Brown, Professor and Graduate Dean
3. Dr. Atsushi Sato, Research Scientist, NIED, Shinjo, Japan

3.0 Inventions

None

4.0 Objectives of the Project

This study was funded for the expressed purpose of extending our knowledge about the microstructural properties of snow and how its thermal environment affects these properties. In order to do this effectively several developments were needed. First, a computer formulation had to be developed to enable the determination of three-dimensional microstructural properties from two-dimensional data (such as from thin sections and surface sections). Second, a data base had to be established such that the data could first be used to calibrate the computer software. This data base would also be used to observe how the material microstructure evolves under a specific set of thermal conditions, in this case under uniform and constant temperatures (equitemperature metamorphism). Finally, a third objective was the development of a formulation utilizing the governing physical laws to predict the time dependent change of material microstructure.

5.0 Summary of Results

The first year of the project (3/1994 - 3/1995) was directed at performing an experimental investigation of equitemperature metamorphism of very fine-grained snow in order to document the changes in the material microstructure (grain size, densification, intergranular bonding, grain shape, etc.) so that a data base could be made available for studying this process. A Japanese scientist, Dr. Atsushi Sato, was brought to Bozeman to work with the principal investigator. Special instrumentation developed by Sato was used to produce fine-grained snow with a predominantly spherical particle shape. Studies were carried out during that year, and the data obtained from that study has been analyzed to determine just how the microstructure changes with time. The test results obtained to date clearly show that mean grain size increases with time, that intergranular bond size demonstrates initial rapid rates of growth, that the material densifies over time without loads, and that grain shape continues to evolve toward a spherical shape in order to minimize free surface energy.

During the second year (3/1995-3/1996) work was directed at two primary tasks. The first was to finish development of an advanced software package that uses stereology theory and morphology theory to obtain detailed measures of three-dimensional microstructure of the material from the use of thin sections and surface sections. This is essentially completed and has resulted in a couple of papers describing the theory and its application. In conjunction with this development, the data obtained from the previous year was also analyzed with the software. A unique feature of the software is its ability to automatically identify the intergranular bonds and the necked regions connecting the grains as seen in a two dimensional surface section. The formulation is also capable of extracting many three-dimensional features from this two-dimensional information.

A second thrust during the past year has been the development of a mixture theory that utilizes the material microstructure to model equitemperature metamorphism of snow. This theory assumes the material has an initial distribution of grain sizes and an initial distribution of intergranular bond sizes. It models how these grains and bonds interchange mass so that the distribution of grain sizes and bond sizes change with time due to thermodynamic interactions between each other. It is a complicated process to describe, but the computer application of this formulation has provided dramatic evidence of how the initial microstructure affects the rate of metamorphism of the material. For instance, Figure 1 below compares the rate of metamorphism for large-grained snow and fine-grained snow.

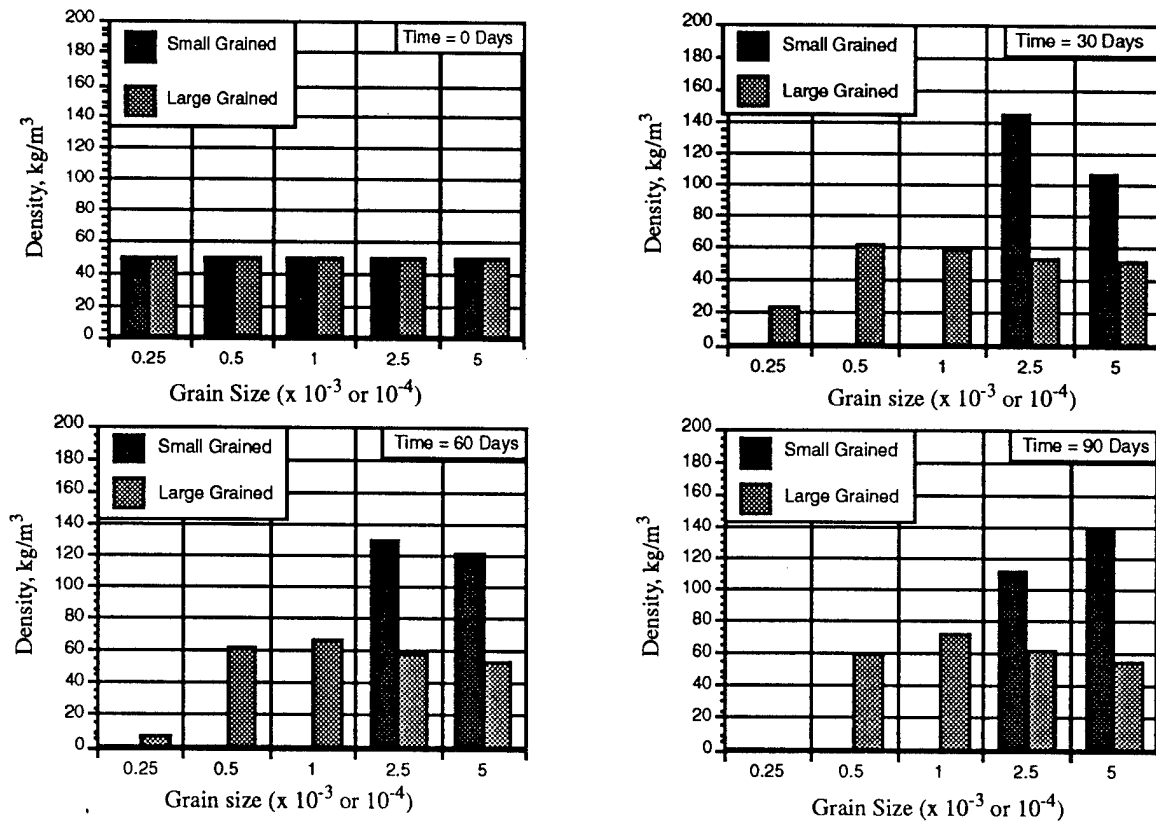


FIGURE 1. Variation of density distribution of constituents with time. The small-grained snow has an initial radii distribution ranging from 0.25×10^{-5} m to 5.0×10^{-4} m. The large-grained snow has a distribution ranging from 0.25×10^{-4} m to 5.0×10^{-3} m, so that each constituent in the large-grained snow is ten times as large as in the small-grained snow.

The large-grained was assumed to have a size distribution consisting of grains with radii of curvature of 0.25, 0.5, 1.0, 2.5 and 5.0 mm, while the fine-grained snow had a distribution of radii of 0.025, 0.05, 0.10, 0.25, and 0.5 mm. In both cases, each grain size had initial densities of 50 kg/m^3 , giving the snow a density of 250 kg/m^3 . The figure demonstrates quite clearly that the fine-grained snow metamorphoses much more quickly than the large-grained snow. The small grains disappear much more quickly and the grain size distribution evolves toward a more uniform grain size with larger grains.

In another example, the formulation was used to investigate the sintering of the material, i.e. the growth of the intergranular bonds which determine much of the mechanical and physical properties of the material (strength, thermal conductivity, viscosity, etc.). The material was assumed to be large-grained with the five grain sizes listed above for the large-grained snow. In addition the bonds were assumed to be distributed such that the bond size was one tenth the size of the grains they were connecting. For example, the grains with a size of 1.0 mm were bonded together with bonds with a 0.1 mm radius. Figure 2 below demonstrate how the theory predicts the growth rate of the bonds with time.

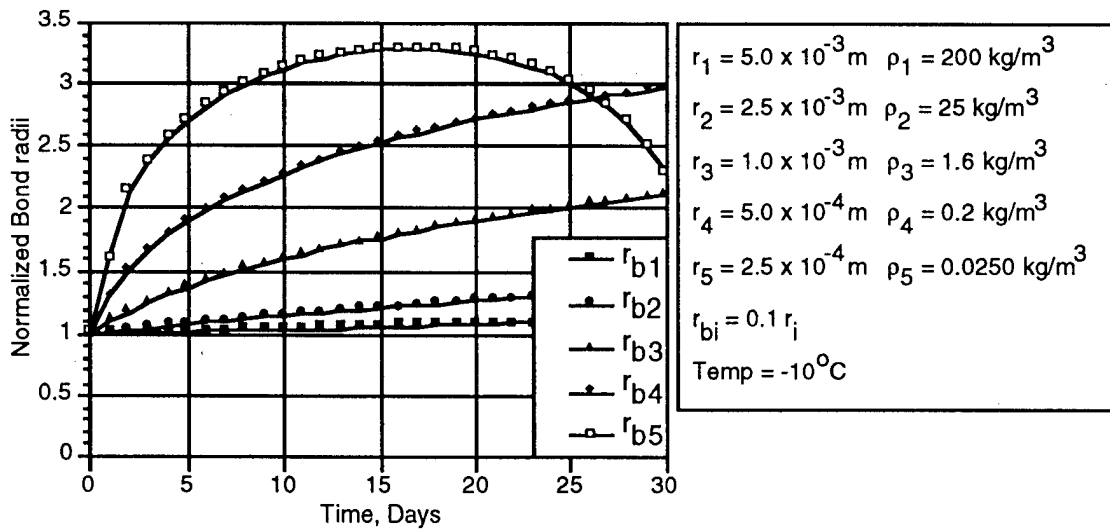


FIGURE 2. Variation of bond dimensions with time.

In this case, the various grain sizes were distributed so that their number densities (number of grains per unit volume) were equal. The smaller bonds are seen to quickly grow. The smallest bond reaches a maximum and then begins to decrease, since these are attached to the grains with an initial size of 0.25 mm, and these grains are being eliminated by losing mass to the larger grains. Consequently the bonds attached to these small grains eventually begin to be eroded along with the grains to which they are attached.

In conclusion, the mixture theory appears to have the capability of modeling equitemperature metamorphism. This will give one the capability to more accurately determine how the mechanical and physical properties evolve with time under certain thermal conditions. This development should provide for a better understanding of metamorphism processes and also provide a basis for the development of physical models for describing response of snow to more general conditions.

Some results of the experimental program can also be shown at this point. The following two figures demonstrate some of the results obtained from the stereology software developed during this grant. The figures are for an experimental study conducted by the PI, Dr. Sato and a Ph.D. student funded by this grant. In this study, artificially fine-grained snow was manufactured and stored at -10°C for a period of about one month. This snow is extremely fine-grained when manufactured, having an initial mean grain size of approximately $30 \mu\text{m}$. This small size has the advantage of having tremendous surface energies, thereby causing metamorphism to proceed much more quickly than for large-grained snow. As a consequence, measurable changes can be observed in much shorter periods than for larger grained snow. Surface sections were analyzed with the stereology software to determine changes in the microstructure of the material. The following two graphs show the time-wise change of the grain size and the bond size.

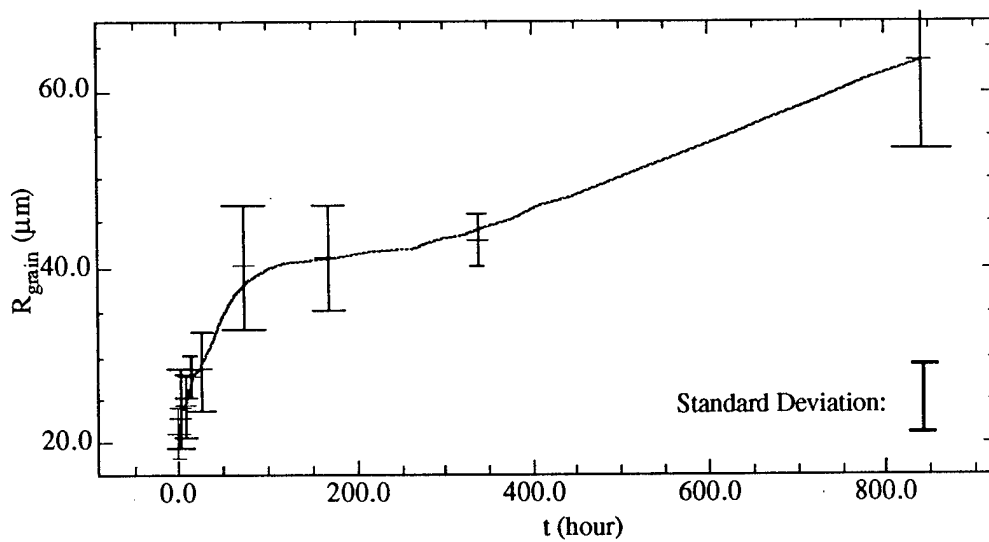


FIGURE 3. Changes in mean grain size during equitemperature conditions at -10°C .

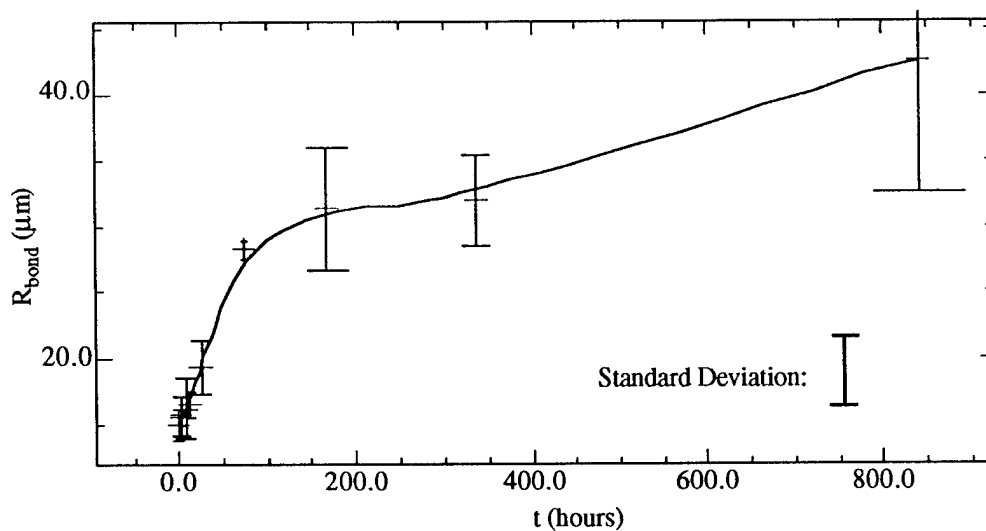


FIGURE 4. Changes in mean bond size during equitemperature conditions at -10°C .

The last period of the grant (3/1996 - 12/1996) has been devoted to refining the stereology software to make it more robust for calculating material microstructure. Additional work has also been directed at extending the mixture theory to look at heat and mass exchange in layered and nonhomogeneous snow under uniform temperature conditions. Work is just now being completed on this aspect of the modeling, and results to date look very good. The theory appears to accurately predict trends in intergranular bonding and grain growth that has been observed in the experimental part of the project. The results of this work will be forthcoming in a series of publications.

6.0 Technology Transfer

The results of this work will be provided to the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). In particular, personnel at CRREL are interested in incorporating some of the features of the stereology software into similar software at that laboratory. They have a very comprehensive software package which is capable of providing a considerable amount of information on snow microstructure. What has been developed in this grant should be a good addition to the capabilities already at CRREL.

7.0 Importance of Research to Army Mission

The technology developed here will enable army personnel to better predict performance of processed snow for snow roads and air strips in polar and alpine regions. The stereology theory developed here will also provide the military with an enhanced capability to evaluate material microstructure of geologic materials and such advanced materials as metal powder compacts. The microstructure is a major factor in determining mechanical and physical properties of these porous and granular materials. This work also has relevance to such problems as snow slope stability for avalanche initiation and the response of the polar ice caps to global climate change. The Antarctic firm, which may be on the order of 100 m thick consists of snow which insulates the ice cap from the atmosphere. How this firm responds to global warming determines the fate of these ice masses. The work here has direct applicability to a better ability to predict the firm response to warming.